

High-proper-motion white dwarfs and halo dark matter

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ABSTRACT

The interpretation of the old, cool white dwarfs recently found by Oppenheimer et al. is still controversial. Whereas these authors claim that they have finally found the elusive ancient-halo white dwarf population that contributes significantly to the mass budget of the galactic halo, there have been several other contributions that argue that these white dwarfs are not genuine halo members but, instead, thick-disc stars. We show here that the interpretation of this sample is based on the adopted distances, which are obtained from a colour–magnitude calibration, and we demonstrate that when the correct distances are used a sizeable fraction of these putative halo white dwarfs belong indeed to the disc population. We also perform a maximum likelihood analysis of the remaining set of white dwarfs and we find that they most probably belong to the thick-disc population. However, another possible explanation is that this sample of white dwarfs has been drawn from a 1 : 1 mixture of the halo and disc white dwarf populations.

Key words: stars: luminosity function, mass function – white dwarfs – Galaxy: halo – Galaxy: stellar content – Galaxy: structure – dark matter.

1 INTRODUCTION

White dwarfs are the most common end-points of stellar evolution. Since they are long-lived and well-understood objects, they constitute an invaluable tool to study the evolution and structure of our Galaxy in general and of the Galactic halo in particular (Isern et al. 1998a). Moreover, the discovery of microlenses towards the Large Magellanic Cloud (Alcock et al. 2000; Lasserre et al. 2001) has generated much controversy about the possibility that white dwarfs could be responsible for these microlensing events and, thus, could provide a significant contribution to the mass budget of our Galactic halo. However, white dwarfs as viable dark matter candidates are not free of problems, since an excess of them would imply as well an overproduction of red dwarfs and Type II supernovae. In order to overcome this problem Adams & Laughlin (1996) proposed a non-standard initial mass function in which the formation of both low- and high-mass stars was suppressed. Besides the lack of evidence for such biased initial mass functions, they also present additional problems. The formation of an average-mass ($\sim 0.6 M_{\odot}$) white dwarf is accompanied by the injection into the interstellar medium of a sizeable amount of mass (typically $\sim 1.5 M_{\odot}$) per white white dwarf.

Since in turn Type II supernovae are suppressed in biased initial mass functions, there is not enough energy to eject this matter into the intergalactic medium and a mass that is roughly three times the mass of the resulting white dwarf has to be accommodated within the Galaxy (Isern et al. 1998a). Furthermore, the mass ejected in the process of formation of a white dwarf is significantly enriched in metals (Gibson & Mould 1997; Abia et al. 2001). Finally, an excess of white dwarfs may translate into an excess of binaries containing such stars. If there are many white dwarfs in binaries then the secondary cannot be a red dwarf because these would be easily detected. Therefore, we are then forced to assume that these binaries are double degenerates, which are one of the currently proposed scenarios for Type Ia supernovae. Hence we are forced to face the subsequent increase of Type Ia supernova rates which, consequently, results in an increase in the abundances of the elements of the iron peak (Canal, Isern & Ruiz-Lapuente 1997). However, other explanations, such as self-lensing in the LMC (Wu 1994; Salati et al. 1999), or background objects (Green & Jedamzik 2002) are possible and have not been yet totally ruled out.

The debate regarding whether or not white dwarfs contribute significantly to Galactic halo dark matter has motivated a large number of observational searches (Ibata et al. 1999; Knox, Hawkins & Hambly 1999; Majewski & Siegel 2002; Nelson et al. 2002; Oppenheimer et al. 2001) and theoretical works (Reylé, Robin &

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Créze 2001; Flynn, Holopainen & Holmberg 2002; Koopmans & Blandford 2002) and is still open. Among the observational surveys perhaps the most extensive one is that of Oppenheimer et al. (2001), who discovered 38 faint white dwarfs with large proper motions in digitized photographic plates from the Super COSMOS Sky Survey. Oppenheimer et al. (2001) claimed that these white dwarfs are indeed halo white dwarfs since they have very large tangential velocities (in excess of $\sim 100 \text{ km s}^{-1}$). Based on this assumption, they derived a space density of 2 per cent of the Galactic dark halo density, which is smaller than previous claims (Alcock et al. 1997) for halo dark matter in the form of $\approx 0.5\text{-}M_{\odot}$ objects, but still significant. However, Reid, Sahu & Hawley (2001) challenged this claim by noting that the kinematics of these white dwarfs is consistent with the high-velocity tail of the thick disc. Hansen (2001) provided evidence that this sample presents a spread in age that makes it more likely to belong to the thick-disc population. Reylé et al. (2001) and Flynn et al. (2002) also support this interpretation. Koopmans & Blandford (2002) find that the contribution of these white dwarfs to the local-halo dark matter density is smaller, of the order of 0.8 per cent, which is in good agreement with the theoretical results of Isern et al. (1998b) and the observational findings of the EROS team (Goldman et al. 2002). In this paper we reexamine this issue by making use of a Monte Carlo simulator (Torres, García-Berro & Isern 1998; García-Berro et al. 1999). The paper is organized as follows. In Section 2 we present the main properties of our Monte Carlo simulator. In Section 3 we discuss the effect of the colour-magnitude calibration on the distances of the white dwarfs in the sample of Oppenheimer et al. (2001), whereas in Section 4 we analyse what the probability is of this sample being drawn from a halo population. Finally, in Section 5 our conclusions are summarized.

2 THE MODEL

A full description of our Monte Carlo simulator can be found in García-Berro et al. (1999). Therefore we will only summarize here the most important inputs. Our model includes two components: the disc and the stellar halo. We start with the disc model. First, masses and birth times are drawn according to a standard initial mass function (Scalo 1998) and an exponentially-decreasing star-formation rate per unit surface area (Bravo, Isern & Canal 1993; Isern et al. 1995). The spatial density distribution is obtained from a scale height law (Isern et al. 1995) that varies with time and is related to the velocity distributions – see below – and an exponentially-decreasing surface density in the Galactocentric distance. The velocities of the simulated stars are drawn from Gaussian distributions. The Gaussian distributions take into account both the differential rotation of the disc and the peculiar velocity of the Sun (Dehnen & Binney 1998a). The three components of the velocity dispersion (σ_U , σ_V , σ_W) and the lag velocity V_0 are not independent of the scale height but, instead, are taken from the fit of Mihalas & Binney (1981) to main sequence star counts. It is important to realize at this point that with this description we recover both the thick- and the thin-disc populations, and, moreover, we obtain an excellent fit to the disc white dwarf luminosity function (García-Berro et al. 1999). For the stellar-halo model, we adopt a spherically-symmetric stellar halo with a density profile given by the expression

$$\rho = \rho_0 \left(\frac{R_{\odot}}{r} \right)^{\gamma}, \quad (1)$$

where ρ_0 is the local density of the halo, $\gamma = 3.4$, and $R_{\odot} = 8.5 \text{ kpc}$ is the Galactocentric distance of the sun. The velocity distributions are Gaussian:

$$f(v_r, v_{\theta}, v_{\phi}) = \frac{1}{(2\pi)^{3/2}} \frac{1}{\sigma_r \sigma_t^2} \exp \left[-\frac{1}{2} \left(\frac{v_r^2}{\sigma_r^2} + \frac{v_{\theta}^2 + v_{\phi}^2}{\sigma_t^2} \right) \right]. \quad (2)$$

The radial and tangential velocity dispersions are determined from Marković & Sommer-Larsen (1997). For the radial velocity dispersion we have

$$\sigma_r^2 = \sigma_0^2 + \sigma_+^2 \left[\frac{1}{2} - \frac{1}{\pi} \arctan \left(\frac{r - r_0}{l} \right) \right], \quad (3)$$

where $\sigma_0 = 80 \text{ km s}^{-1}$, $\sigma_+ = 145 \text{ km s}^{-1}$, $r_0 = 10.5 \text{ kpc}$ and $l = 5.5 \text{ kpc}$. The tangential dispersion is given by

$$\sigma_t^2 = \frac{1}{2} V_c^2 - \left(\frac{\gamma}{2} - 1 \right) \sigma_r^2 + \frac{r}{2} \frac{d\sigma_r^2}{dr}, \quad (4)$$

where

$$r \frac{d\sigma_r^2}{dr} = -\frac{1}{\pi} \frac{r}{l} \frac{\sigma_+^2}{1 + [(r - r_0)/l]^2}. \quad (5)$$

For the calculations reported here we have adopted a circular velocity $V_c = 220 \text{ km s}^{-1}$.

The halo was assumed to be formed in an intense burst of star formation that occurred 14 Gyr ago and lasted 1 Gyr. Regarding the cooling sequences, we adopt those of Salaris et al. (2000), which incorporate the most accurate physical inputs for the stellar interior and reproduce the blue turn-off due to the hydrogen opacity (Hansen 1999) at low luminosities. We use the transformations of Bessell (1986) and Blair & Gilmore (1982) to convert the colours of the atmospheres of Saumon & Jacobson (1999) to the photographic colours used by Oppenheimer et al. (2001). Main sequence lifetimes and the initial-mass/final-mass relationship for white dwarfs are as in García-Berro et al. (1999). The initial mass function adopted for the halo is the same as for the disc simulations (Scalo 1998). Finally, the observational selection criteria adopted in order to draw white dwarfs from the Monte Carlo simulated populations are the same as used by Oppenheimer et al. (2001), namely, $0.16 \text{ arcsec yr}^{-1} \leq \mu \leq 10.0 \text{ arcsec yr}^{-1}$ in proper motion, $16.6 \text{ mag} \leq R_{59F} \leq 19.8 \text{ mag}$ in apparent magnitude, distances $d \leq 200 \text{ pc}$ and $4900 \text{ square degrees}$ in the direction of the South Galactic Cap.

3 THE COLOUR-MAGNITUDE CALIBRATION

Oppenheimer et al. (2001) used the observational data of Bergeron, Ruiz & Leggett (1997) to obtain an empirical calibration of the absolute M_{B_J} magnitude from the $B_J - R_{59F}$ colour index and from it the distances of the white dwarfs. In the top panel of Fig. 1 we show this calibration as a dashed line. The white dwarfs of the sample of Oppenheimer et al. (2001) are represented as triangles. Also shown in this panel is the result of a typical Monte Carlo simulation of the halo white dwarf population (circles) and the cooling track of an otherwise typical $0.6\text{-}M_{\odot}$ white dwarf – solid line (Salaris et al. 2000). As can be seen in this figure, there are two prominent features. First, and most importantly, the slope of the calibration of Bergeron et al. (1997) is very different from that of the Monte Carlo simulation. As a result, the distances of the white dwarfs of the sample of Oppenheimer et al. (2001) have been underestimated for bright white dwarfs and overestimated for low-luminosity white dwarfs. Secondly, the presence of the downturn at very low luminosities is clearly seen. For the adopted age of the halo, the turn-off to the blue for the Monte Carlo simulation is located at $B_J - R_{59F} \simeq 1.2$, whereas for a typical $0.6\text{-}M_{\odot}$ white dwarf it is located at $B_J - R_{59F} \leq 1.6$. This is a consequence

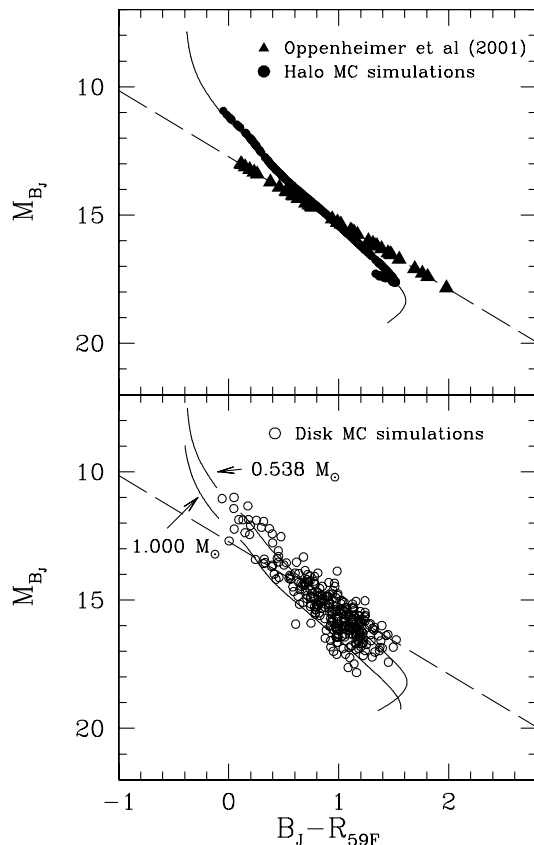


Figure 1. Top panel: the calibration of the M_{B_J} magnitude as a function the $B_J - R_{59F}$ colour index used in Oppenheimer et al. (2001) – dashed line – compared with the cooling track of a $0.6 M_\odot$ white dwarf – solid line – and a typical Monte Carlo simulation of the halo white dwarf population – circles. The white dwarfs in the sample of Oppenheimer et al. (2001) are represented as triangles. Bottom panel: a typical Monte Carlo simulation of the disc white dwarf population. See text for details.

of the adopted age of the halo. Since the halo was assumed to be formed as a burst of star formation, halo white dwarfs are distributed along the colour–magnitude diagram according to their mass, given that the relation $t_{\text{halo}} \simeq t_{\text{MS}}(M) + t_{\text{cool}}(L, M)$ always holds (Isern et al. 1998a). Clearly, the white dwarfs which are beyond the turn-off in the Monte Carlo simulation are massive white dwarfs, which come from massive progenitors with smaller main sequence lifetimes. Nevertheless, the turn-offs of both the Monte Carlo simulation and the cooling track of Salaris et al. (2000) are located at bluer colours than the coolest white dwarfs in the sample of Oppenheimer et al. (2001). Therefore, since these white dwarfs are clearly beyond both turn-offs they cannot be DA white dwarfs.

Now the following question arises: ‘Which process is responsible for the different slopes in the colour–magnitude calibration?’ An idea would be that, in principle, this difference could be ascribed solely to the different physics of the adopted envelopes. The cooling sequences adopted in this work are those of Salaris et al. (2000), which incorporate the most up-to-date atmospheres (Saumon & Jacobson 1999). In Fig. 2 we compare the cooling tracks of Salaris et al. (2000) with the observational data of Bergeron et al. (2001). As can be seen, our cooling sequences compare very favourably with the available observational data both in the colour–colour and

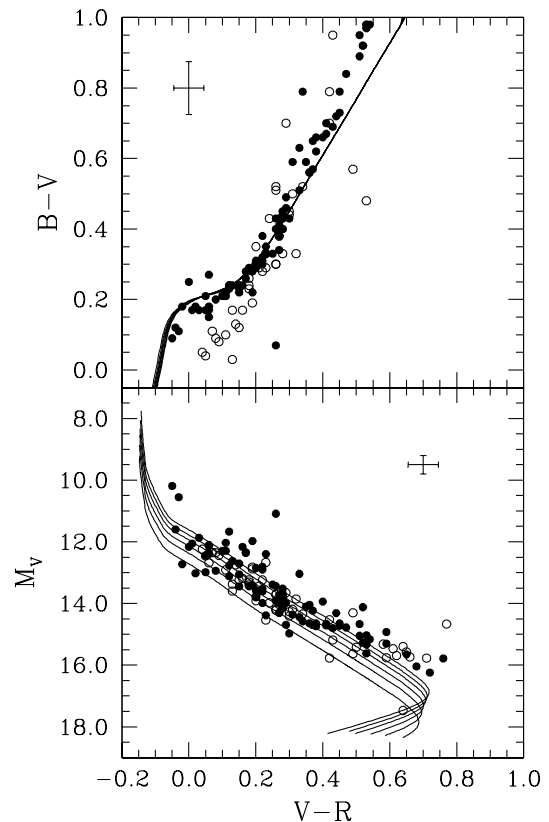


Figure 2. Top panel: colour–colour diagram for the sample of Bergeron et al. (2001). We have chosen this diagram because in these colours the dispersion of the cooling sequences is minimum. The white dwarfs are represented as open symbols whereas filled symbols correspond to white dwarfs with H-rich atmospheres. The cooling tracks of Salaris et al. (2000) for several masses are also shown. Bottom panel: comparison of the cooling tracks of Salaris et al. (2000) with the colour–magnitude diagram of the same sample of old, cool disc white dwarfs. The masses of the cooling tracks are, from top to bottom, 0.54 , 0.61 , 0.68 , 0.87 and $1.0 M_\odot$, respectively. In both panels, typical error bars are shown.

in the colour–magnitude diagram. For instance, most of the over-luminous white dwarfs located above the theoretical cooling track of the $0.54 M_\odot$ model are unresolved binaries and, as discussed in Bergeron et al. (2001), their luminosity comes from the contribution of two otherwise normal white dwarfs. In the colour–colour diagram the agreement is also excellent, especially for $V - R < 0.4$. For $V - R > 0.4$ a slight departure from the observational data is observed, but always within the observational error bars. Again, as discussed in Bergeron et al. (2001), this is a common drawback of all theoretical models and can be explained in terms of a missing opacity source near the B filter in the pure-hydrogen models, most probably due to a pseudocontinuum opacity originating from the Lyman edge. Therefore we conclude that our cooling sequences are in good agreement with the observational data for old, cool disc white dwarfs. Note, however, the excess of overluminous white dwarfs at the red end of the cooling sequences. We shall revisit this issue later.

Although this could indeed be one of the reasons, there is yet another possibility, namely that the calibration of Oppenheimer et al. (2001) is not appropriate for the halo white dwarf population. The reader should take into account that Oppenheimer et al. (2001)

derived the above-mentioned calibration using a sample of cool disc white dwarfs, namely with $M_V > 12$. Note that for $M_V \sim 12$ there is an abrupt change in the slope of the cooling tracks. In this regard, in the bottom panel of Fig. 1 we show the result of a typical Monte Carlo simulation of the disc white dwarf population (open circles) and the calibration used by Oppenheimer et al. (2001). Since they obtained the calibration using white dwarfs with known parallaxes for which the error in the parallax determination was smaller than 30 per cent, we have added a conservative Gaussian error of 20 per cent for the parallaxes of the white dwarfs in this sample. Additionally, a 10 per cent error in the colour index has also been added. There is as well another spread in the photometric calibration which comes from the very different star formation histories of the two populations. Indeed, the disc white dwarf population is obtained from a smoothly-varying star-formation rate that produces massive white dwarfs almost continuously as a consequence of the very-small main sequence lifetimes of their progenitors, whereas, as previously discussed, the halo white dwarf population is distributed according to the mass along the cooling track of a typical $0.6\text{-}M_\odot$ white dwarf. The mass spread is clearly seen in the bottom panel of Fig. 1, where the cooling tracks of Salaris et al. (2000) for 0.538- and $1.0\text{-}M_\odot$ white dwarfs are shown. All these effects force the distribution of disc white dwarfs to have a significant spread in the colour–magnitude diagram. Moreover, as can be seen in this panel, the slope of the calibration of Oppenheimer et al. (2001) could be valid for a randomly-selected sample of cool white dwarfs, i.e. white dwarfs with colours $B_J - R_{59F} \gtrsim 0.5$ or, equivalently, $M_V \gtrsim 12$. In fact, since Bergeron et al. (1997) were selecting cool white dwarfs, namely with $M_V \gtrsim 12$, a shallower slope of photometric calibration would not be very surprising given the observational errors. In order to check this and to make a more quantitative statement we have randomly selected from our simulated samples 80 subsets of 100 white dwarfs, which is the typical size of the sample of Bergeron et al. (1997), with $M_V > 12$. For each of the subsets we have computed the slope of the colour–magnitude calibration and its standard deviation. We obtain a mean slope and a mean standard deviation of 3.18 ± 0.25 for the M_{B_J} versus the $B_J - R_{59F}$ calibration. Here we have used for the mean standard deviation the ensemble average of the individual dispersions for each one of the subsets. This value has to be compared with that adopted by Oppenheimer et al. (2001), namely 2.58, which still is slightly beyond the 2σ confidence interval. Hence, although this is a possible explanation for the discrepancy in the slopes, there may be another effect at the root of this discrepancy.

Indeed, there is another subtle effect that should be taken into account in analysing the colour–magnitude calibration. Note that in the colour–magnitude of Fig. 2 the blue portion of this diagram (say $V - R < 0.4$) is more populated than the red – and, hence, the cool – part of the diagram. The observational disc white dwarf luminosity function shows a monotonic increase all the way to $M_V \simeq 15$ (Leggett, Ruiz & Bergeron 1998), and a sharp drop at $M_V \simeq 16$ as a consequence of the finite age of the disc. Note that the blue turn-off is not visible in the disc white dwarf population since it occurs at even fainter luminosities ($M_V \simeq 18$). Hence, we should expect an increasing number of white dwarfs at red colours. This is not what it is found observationally and, in fact, there is an otherwise natural selection effect against low-luminosity white dwarfs. Moreover, Fig. 2 clearly shows that low-mass white dwarfs, those with $M < 0.54 M_\odot$, are more abundant at the red end of the colour–magnitude diagram. As noted above, these low-mass white dwarfs are members of unresolved binaries, and this explains why they are overluminous. In

turn, the fact that these white dwarfs are overluminous explains why they are more abundant at low luminosities. But this observational bias strongly affects the slope of the colour–magnitude calibration, making it shallower. Moreover, from the theoretical point of view there are as well compelling evidences to exclude these white dwarfs from the colour–magnitude calibration since single low-mass white dwarfs have He cores and their progenitors have not had enough time to evolve off the main sequence. In any case, the important point here is that these overluminous white dwarfs dominate the red portion of the colour–magnitude diagram and, hence, the colour–magnitude calibration. In order to make this argument quantitative we have proceeded as follows. We eliminate from the sample of Bergeron et al. (2001) all white dwarfs with masses smaller than $0.54 M_\odot$, because they are suspected to be unresolved binaries. After that we compute a linear fit to the empirical cooling sequence for $M_V > 12$. We obtain that the slope of the linear fit is 2.95 ± 0.18 , which is in good agreement with the result obtained from the Monte Carlo simulations. In summary, there are clear evidences from both the observational and the theoretical point of view to adopt a steeper colour–magnitude calibration in accordance with the theoretical models. Thus, we conclude that the distances derived for the white dwarfs in the sample of Oppenheimer et al. (2001) should be recomputed using the correct cooling tracks.

The basic argument used by Oppenheimer et al. (2001) to claim that their sample is representative of an ancient-halo white dwarf population was that these white dwarfs have very large tangential velocities. This result is sensitive to the adopted distances. Moreover, since the distances of bright white dwarfs have been overestimated and the distances of dim white dwarfs have been underestimated it is not evident how the colour–magnitude calibration affects the derived tangential velocities. This is assessed in Fig. 3, where the tangential velocities of the white dwarfs of the sample of Oppenheimer et al. (2001) are shown. We followed exactly the same procedure they used. That is, we have assumed null radial velocity. In the top panel of Fig. 3 the velocities obtained using the distances computed from the calibration of Oppenheimer et al. (2001) are shown, whereas in the bottom panel the distances obtained in this work have been used. In the bottom panel of Fig. 3 the white dwarfs which are located beyond the blue turn-off in Fig. 1 have been removed since our cooling sequences are not able to reproduce their position in the colour–magnitude diagram. Also shown in this figure are the velocity ellipsoids for the disc and the halo (at 1σ and 2σ). The velocity ellipsoids for the halo are centred at $(U, V) = (0, -220)$ km s^{-1} . The radius at 1σ is given by $\sigma_U = \sigma_V = V_c/\sqrt{2}$. The velocity ellipsoids for the disc are centred at $(U, V) = (0, -35)$ km s^{-1} . The axis at 1σ are $(\sigma_U, \sigma_V) = (50, 30)$ km s^{-1} (Dehnen & Binney 1998b).

As can be seen in Fig. 3 the resulting tangential velocities are such that a significant fraction of the white dwarfs of the sample of Oppenheimer et al. (2001) move inside the velocity ellipsoid of the disc. Therefore, and following the same criterion used by Oppenheimer et al. (2001) these white dwarfs are not genuine halo members and should be dropped from further analysis.

4 MAXIMUM LIKELIHOOD ANALYSIS OF THE SAMPLE

Now we concentrate our efforts on performing a maximum likelihood analysis of the potential halo white dwarf candidates found in the sample of Oppenheimer et al. (2001). In order to do so we use the following procedure. First it should be noted that Oppenheimer

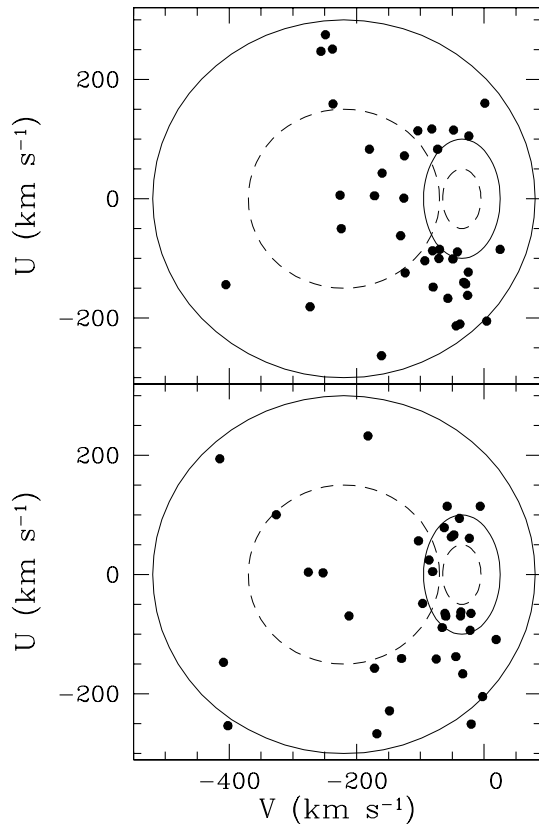


Figure 3. Panels showing the tangential velocities of the white dwarfs of the sample of Oppenheimer et al. (2001). In the top panel the velocities obtained using the distances obtained from their calibration are shown, whereas in the bottom panel the distances obtained in this work have been used. We have also assumed null radial velocity as Oppenheimer et al. (2001) did. See text for further details.

et al. (2001) disregarded all white dwarfs situated inside the 2σ disc contour of Fig. 3. As previously stated, we follow exactly the same criterion. There are 23 white dwarfs for which the distances derived here are beyond the 2σ contour of the disc velocity ellipsoid. These white dwarfs are represented as large filled circles in Fig. 4. Of these white dwarfs there are eight that are located in the region between the 2σ and 4σ contours (shown in Fig. 4 as a long-dashed line) of the disc population. That is, there are eight white dwarfs located in what we can call the most extreme tail of the thick-disc distribution. We generate Monte Carlo simulations for both the disc and the halo, with exactly the same restrictions in magnitude and proper motion adopted by Oppenheimer et al. (2001) and located in the same region of the sky. These simulations are shown in Fig. 4 as small open circles. The number of stars in both simulations is very large (of the order of $\sim 10^4$) but, for the sake of clarity, only a small fraction of randomly-selected white dwarfs has been represented in these diagrams. From these simulations we extract a subset of 23 white dwarfs. Then we count how many white dwarfs of this subset are located in the region between the 2σ and 4σ contours. Let us call this number n . We repeat the process iteratively many times, of the order of $N = 10^6$, until significant statistics are achieved and we compute the number of times N_n that we find n white dwarfs in this region. The probability of n stars to be located in this region of the diagram (between the 2σ and 4σ contours) is then $P = N_n/N$. We compute this probability for both the halo simulation and the disc simulation.

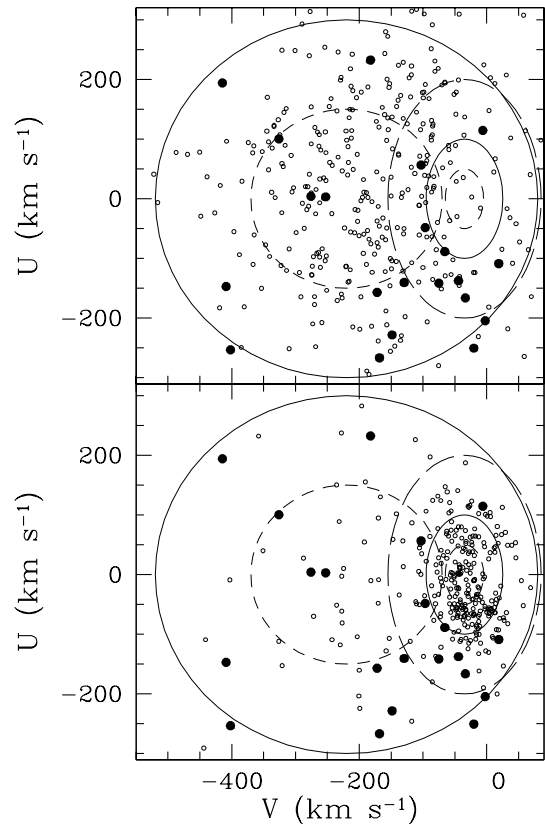


Figure 4. The distribution of tangential velocities of the white dwarfs of the sample of Oppenheimer et al. (2001) – filled symbols – compared with the results of a typical Monte Carlo simulation – open symbols – of the halo (top panel), and of the disc (bottom panel). We have adopted our revised distances to the white dwarfs of Oppenheimer et al. (2001) in computing their velocities.

The probabilities computed with the above-explained procedure are shown in the top panel of Fig. 5. As can be seen in this panel, both distributions of normalized probabilities are Gaussian to a good approximation. The distribution of probabilities for the halo (left histogram) is centred at $n = 5$, whereas the corresponding distribution for the disc is centred at $n = 15$. Their full widths at half maximum are, respectively, $\simeq 4$ and $\simeq 5$. The number of white dwarfs in the sample of Oppenheimer et al. (2001) located in this region is marked as a thin-dashed line. It is thus difficult to ascertain whether or not the sample of Oppenheimer et al. (2001) belongs to the halo population or to the disc population. In fact it would be possible for this sample to contain stars from the tails of both populations. This is important since, in contrast to what happens with main sequence stars, whose metallicity is a good indicator of the population to which they belong, for the case of white dwarfs we do not have any way to ascertain whether a white dwarf belongs to the thick- or to the thin-disc population, except for its kinematics. Most importantly, this result taken at face value implies that the sample of Oppenheimer et al. (2001) cannot be uniquely assigned at the 95 per cent confidence level to either of the two populations *as a whole*. Moreover since the fraction of thick-disc stars is small in a randomly-selected sample of disc white dwarfs, it is not obvious from the simulations presented here that the sample of Oppenheimer et al. (2001) belongs to the thick disc. Since our model for the disc white dwarf population recovers naturally both the thick- and the

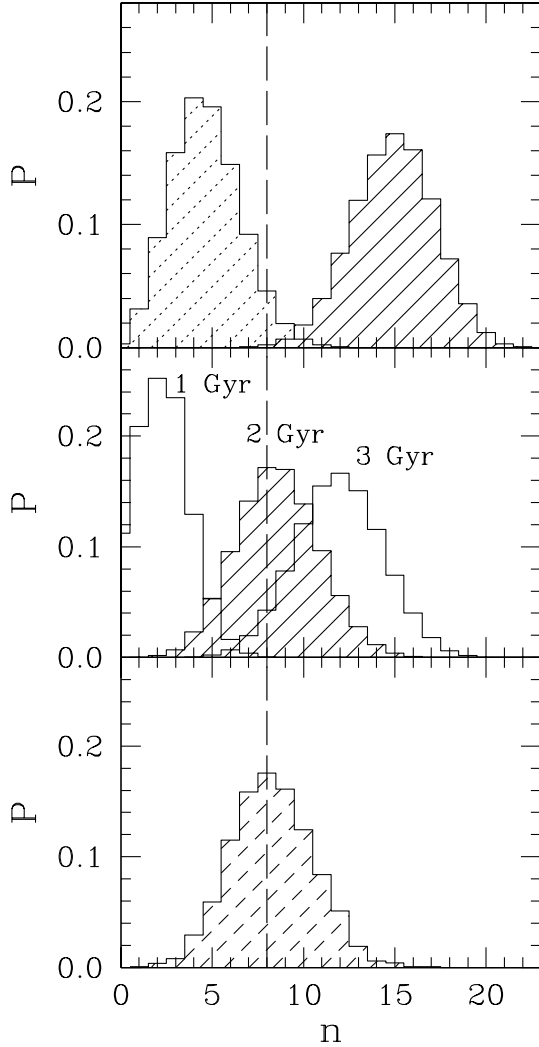


Figure 5. Distribution of normalized probabilities that the white dwarfs of the sample of Oppenheimer et al. (2001) are drawn from the disc and halo simulations shown in Fig. 4. The left diagram of the top panel corresponds to the halo population whereas the right diagram corresponds to the disc simulation. The three histograms of the central panel correspond to the stars that were born in the very early stages of the life of the disc of our Galaxy (1, 2 and 3 Gyr, respectively). Finally, the bottom panel displays the normalized probability distribution for a 1 : 1 mixture of halo and disc stars.

thin-disc white dwarf populations as a function of the birth time of the progenitor stars, we have binned the stars as a function of their age. The stars belonging to the thick-disc population are those with birth times smaller than say $\simeq 2$ Gyr. The resulting distributions of velocities are shown in Fig. 6, where the white dwarfs with progenitors with birth times smaller than 1 and 2 Gyr are shown (top and bottom panel, respectively).

As can be seen in this figure, the stars which were born in the very early stages of the life of our Galaxy have on average larger tangential velocities than the whole white dwarf population, as expected. Now we perform the same probability analysis for these subsets of the disc white dwarf population. The resulting probability distributions are shown in the middle panel of Fig. 5 for 1, 2 and 3 Gyr. Each histogram is labelled with the corresponding age. Obviously, the most probable number of white dwarfs found in the region between the 2σ and 4σ contours of the disc decreases as the mean

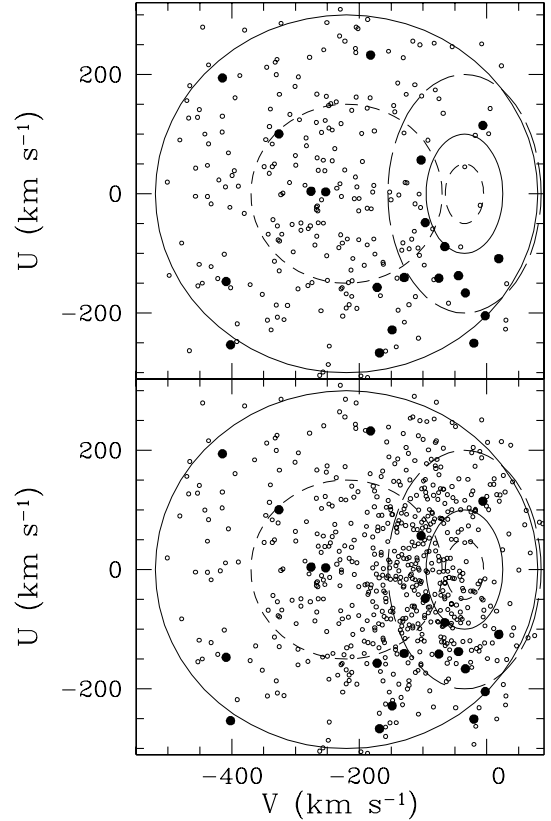


Figure 6. Panels showing the distribution of tangential velocities of the white dwarfs of the sample of Oppenheimer et al. (2001) – filled symbols – compared with the disc white dwarf stars with birth times smaller than 1 Gyr (top panel) and 2 Gyr (bottom panel) obtained in a typical Monte Carlo simulation.

age considered decreases. However, as clearly seen in this panel, thick-disc stars are able to reproduce the number of stars found in this region. In particular, if we adopt an age cut of 2 Gyr, the number of white dwarfs in the region between the 2σ and 4σ disc contours is nicely reproduced.

However, there is yet another possibility, namely that the sample of Oppenheimer et al. (2001) corresponds to a randomly-selected mixture of both the halo and the disc populations shown in Fig. 4. This is assessed in the bottom panel of Fig. 5 where we show the probability distribution for such a mixture of both disc and halo white white dwarfs with equal proportions. As can be seen, there the probability of finding eight white dwarfs in the above-mentioned region is maximum for such a fraction. Therefore, it is quite likely as well that the sample of Oppenheimer et al. (2001) would contain white dwarfs coming from both populations (thick-disc and halo) and that the respective ratio is 1 : 1.

Finally, we have computed the number density of halo white dwarfs of the sample of Oppenheimer et al. (2001) with the new distances derived in this work and compared it with previous works, as shown in Table 1. In doing so, we have used the V_{\max}^{-1} method (Schmidt 1968). The derived number density of this sample is $n = 6.2 \times 10^{-5} \text{ pc}^{-3}$. According to the previous discussion, this density is an upper limit to the density of halo white dwarfs. This number should be compared with the density originally derived by Oppenheimer et al. (2001), which is $n = 2.2 \times 10^{-4} \text{ pc}^{-3}$, which is a factor of 3.5 larger, with the density derived using a neural network

Table 1. Number density of the halo white dwarf population.

Author	n (pc ⁻³)
Oppenheimer et al. (2001)	2.2×10^{-4}
Torres et al. (1998)	1.2×10^{-5}
Gould et al. (1998)	2.2×10^{-5}
This work	3.1×10^{-5}

to identify possible halo candidates by Torres et al. (1998), which is $n = 1.2 \times 10^{-5}$ pc⁻³, and with the density derived by Gould, Flynn & Bahcall (1998) using subdwarf stars, which is $n = 2.2 \times 10^{-5}$ pc⁻³. Clearly, the local density derived in this work is in good agreement with previous independent determinations. Moreover, if we assume that only one out two white dwarfs is a genuine member of the halo white dwarf population, as suggested by our Monte Carlo simulations, we derive a number density of 3.1×10^{-5} pc⁻³, which is very close to the number density of Gould et al. (1998).

5 CONCLUSIONS

We have presented evidence that the distances of the white dwarfs in the sample of Oppenheimer et al. (2001) have not been correctly determined. The ultimate reason for this is that the authors used a calibration that is not appropriate for the halo white dwarf population. Once the correct calibration is adopted it turns out that the distances to the most luminous white dwarfs in the sample have been underestimated, whereas the distances to the white dwarfs with small luminosities have been overestimated. We have also found that some white dwarfs in the sample cannot have hydrogen-dominated atmospheres, since their position in the colour–magnitude diagram is beyond the turn-off. As a consequence, once the corrected distances are taken into account, a good fraction of these putative halo white dwarfs have significantly smaller tangential velocities and can be safely discarded as genuine halo members.

The remaining fraction of the sample of Oppenheimer et al. (2001) has been analysed using our Monte Carlo simulator. We have computed Monte Carlo models for the disc and the halo populations. The disc simulation naturally recovers both the thin- and the thick-disc populations. Then we have computed the probability that the stars of the sample of Oppenheimer et al. (2001) belong to a randomly-selected sample of both halo or disc white dwarfs. Our results indicate that this subset of the sample of Oppenheimer et al. (2001) does not belong exclusively to either the halo or the disc population at the 95 per cent confidence level. Regarding the disc population *as a whole*, our results were not conclusive because of the small fraction of thick-disc stars in a typical Monte Carlo simulation. However, once the stars with small birth times ($\lesssim 2$ Gyr), corresponding to the thick disc, are selected we find that the number of stars in the sample nicely reproduces the values found by Oppenheimer et al. (2001), in agreement with the results of Flynn et al. (2002) and Reyl   et al. (2001). There is yet another possibility that has not been previously explored. Namely that the sample of Oppenheimer et al. (2001) is drawn from a mixture of both the halo and the (thick-) disc populations. We have found that in this case the probability is maximum for a 1 : 1 ratio. Hence, we conclude that the claim by Oppenheimer et al. (2001) that, finally, the elusive halo white dwarf population has been found should be taken with caution and more observational searches and theoretical work are still needed. Finally we have re-derived, using the distances obtained in this work, the number density of halo white dwarfs predicted by the sample of

Oppenheimer et al. (2001). We have found that a safe upper limit to this density is $n = 6.2 \times 10^{-5}$ pc⁻³, assuming that *all* the white dwarfs found by Oppenheimer et al. (2001) are true halo white dwarfs. If, as suggested by our simulations, we assume that only half of these stars are genuine halo members, we find a number density of 3.1×10^{-5} pc⁻³, which is in good agreement with previous independent determinations.

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